Advanced Reciprocating Engines

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Background

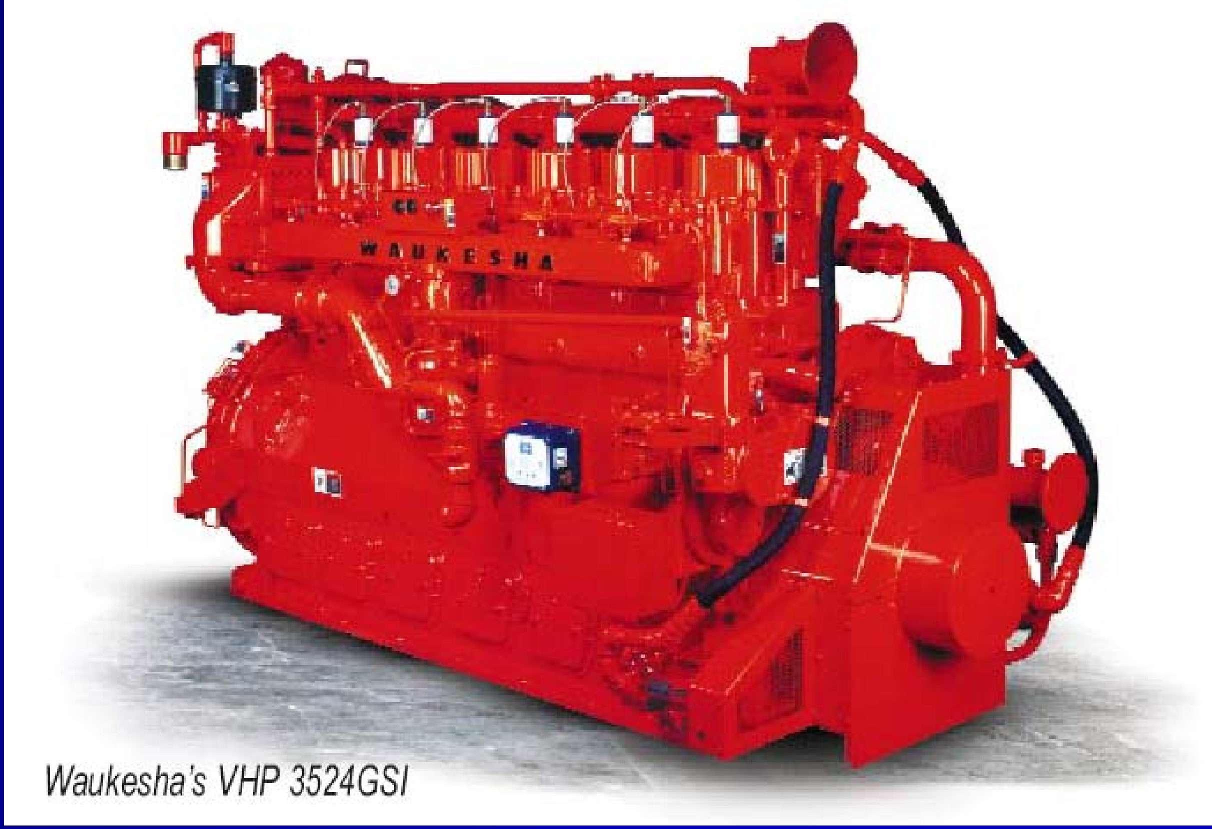
- US power generation capacity is increasing ~2.6% annually (Worldwide ~ 3%)
- Much of this power is large turbines, but reciprocating engines play an important role for distributed resources
- Climate change has placed an emphasis on efficiency (CO_2), while air quality issues have placed an emphasis on NO_x
- Natural gas engines have potential to fulfill the market requirements for low NOx and high efficiency

Background (2)

- Development efforts to improve the performance and emission to unprecedented levels are on-going
- Two notable U.S. efforts are
  - ARES - Advanced Reciprocating Engine Systems, sponsored by the U.S. Department of Energy
  - ARICE - Advanced Reciprocating Internal Combustion Engine, sponsored by the California Energy Commission

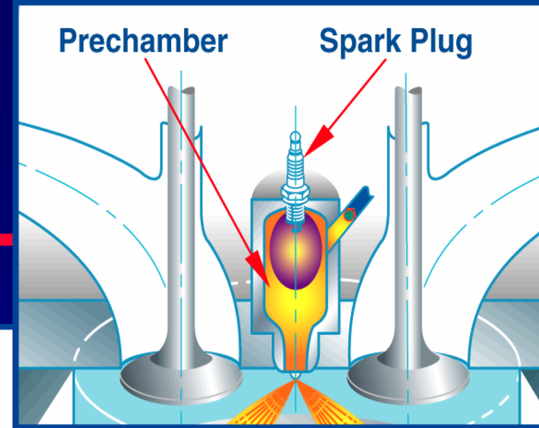
Why reciprocating engines?

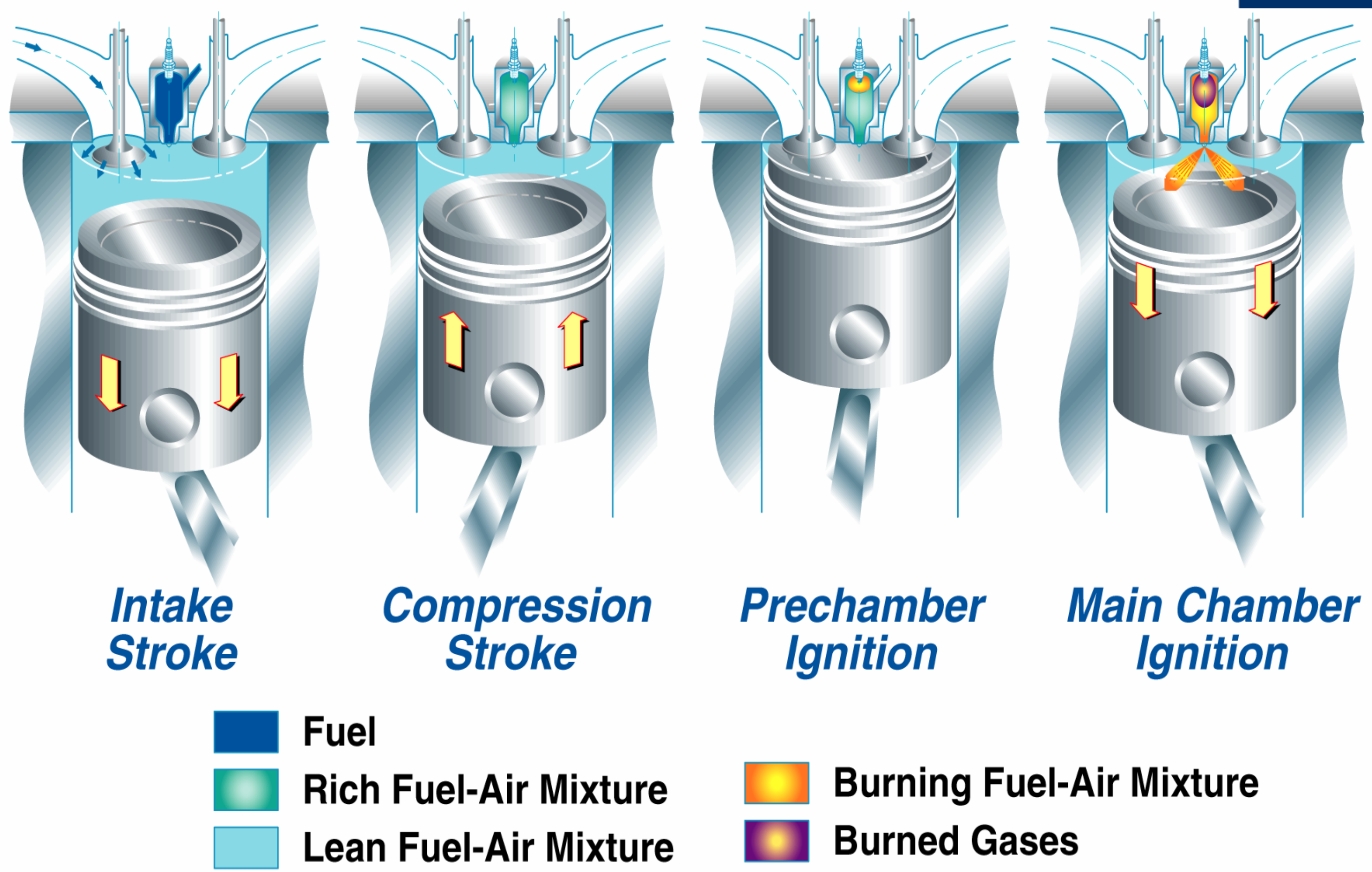
- Cost
- Flexibility
- Reliability
- Efficiency



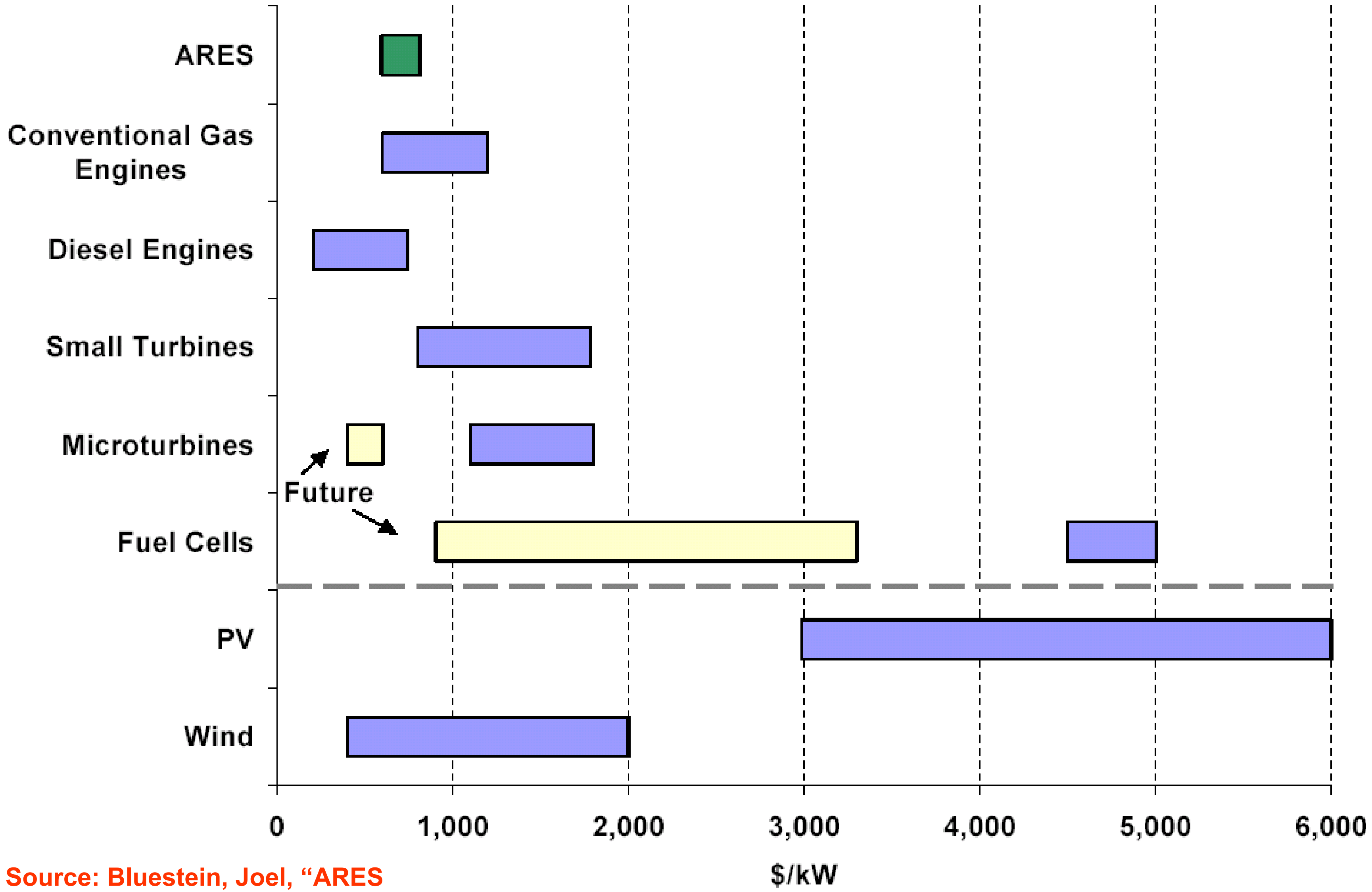
Waukesha's VHP 3524GSI

Spark-Ignited, Prechamber, Natural Gas Engine Combustion Concept





Installed Cost Comparison



Source: Bluestein, Joel, "ARES Engine Market Assessment", ARES Peer Review, April 2002

Engines come in various sizes...

- Small Engines

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- Light Duty

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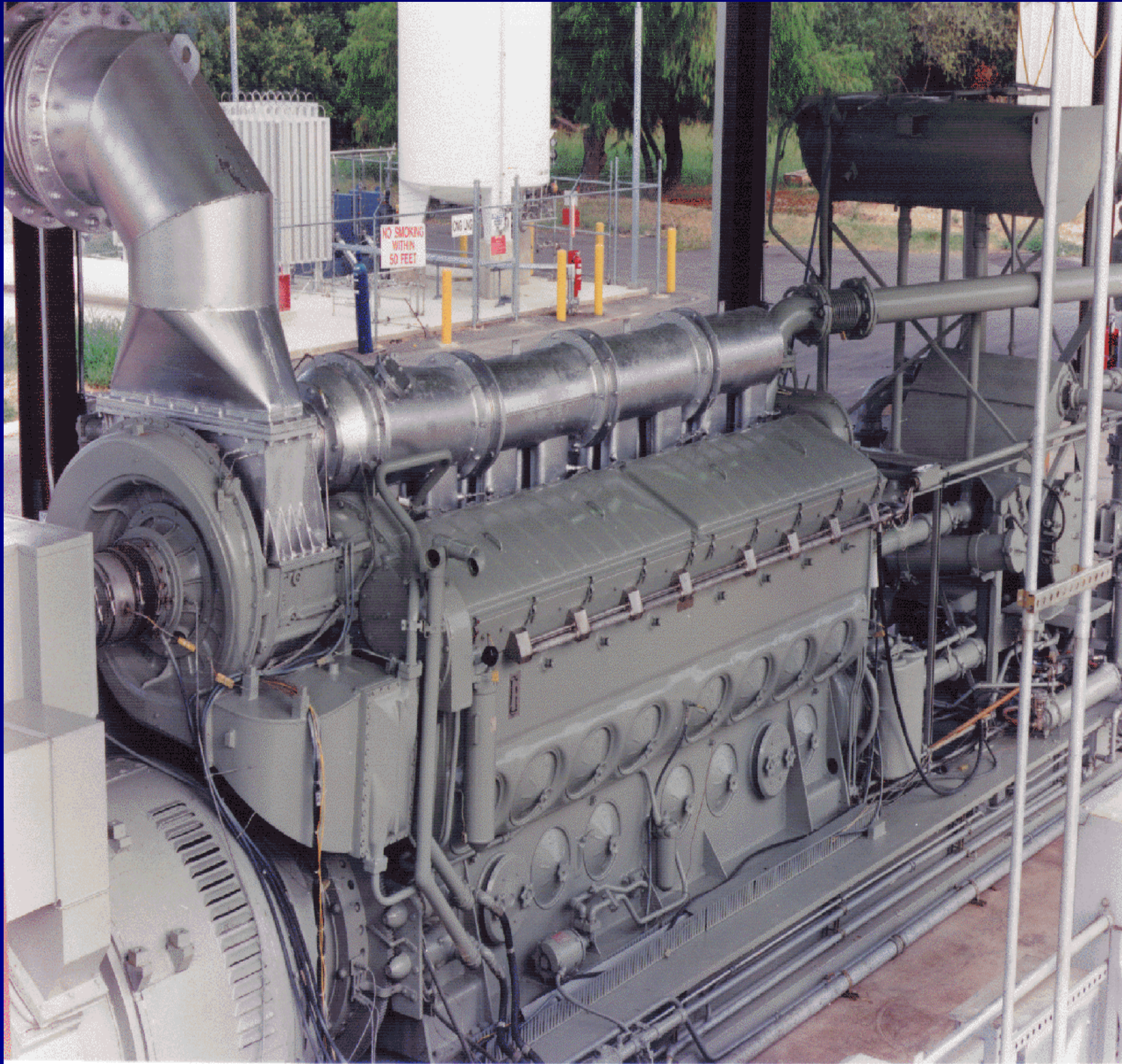
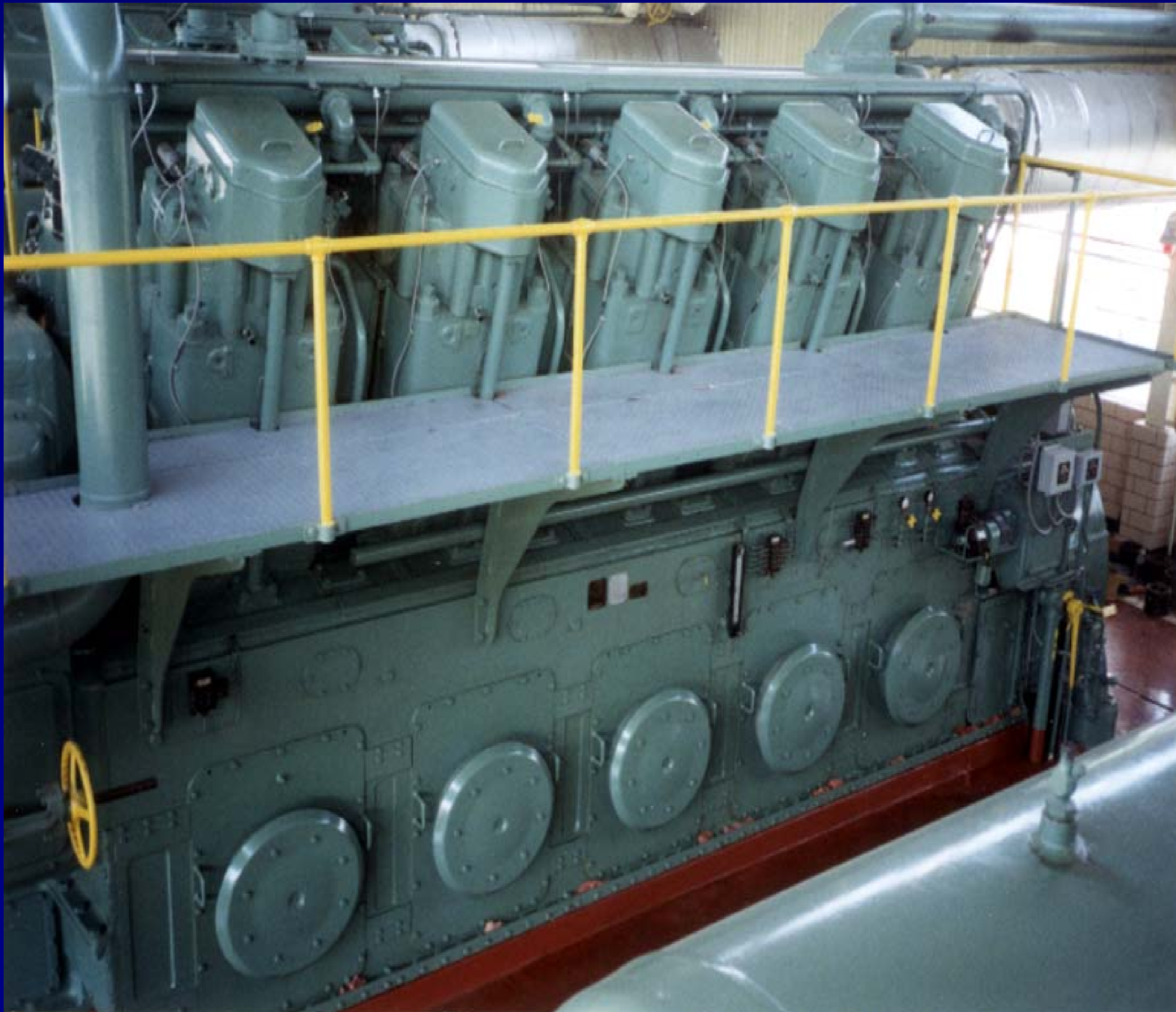
- **Locomotive**



Engines come in various sizes...

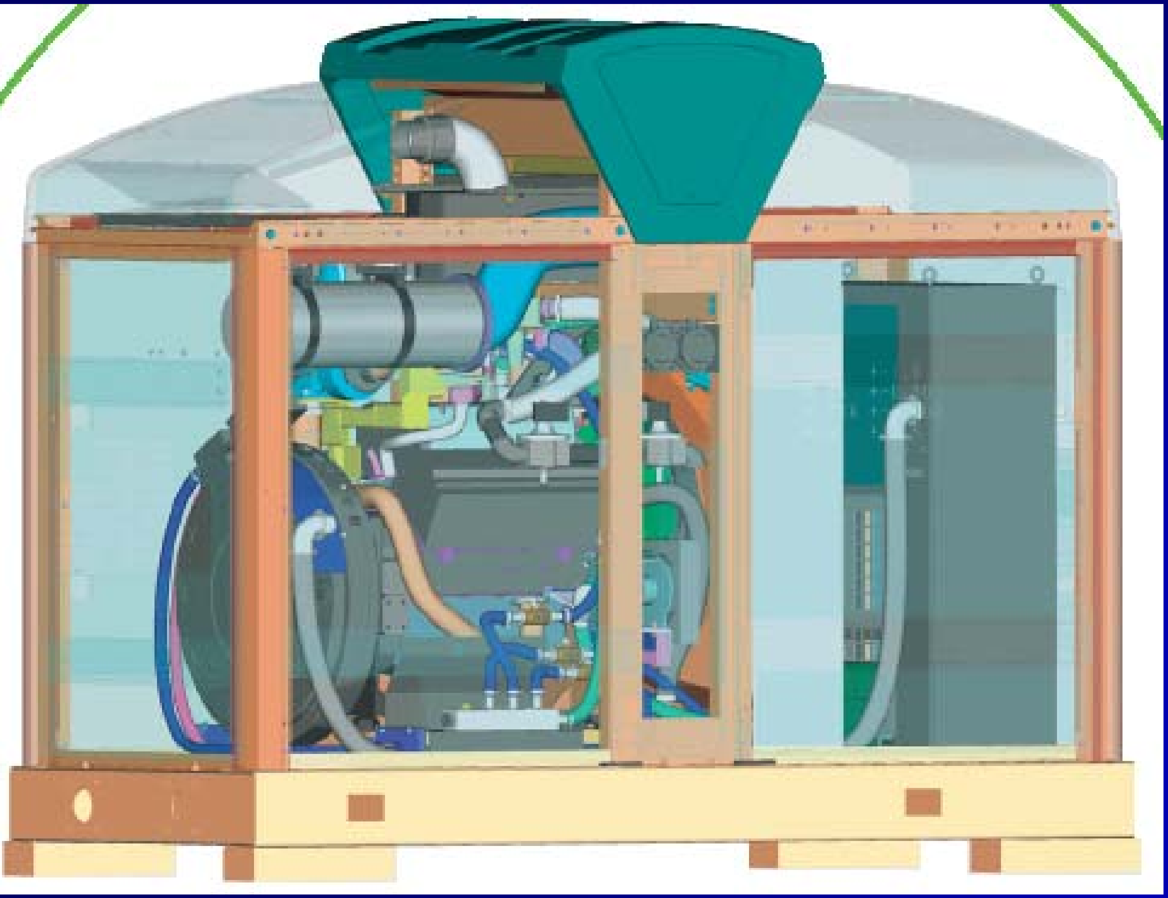
- Small Engine
- Light Duty
- Heavy Duty
- Locomotive
- **Stationary**



Engine Piston Comparison

Scale

150 kW Genset

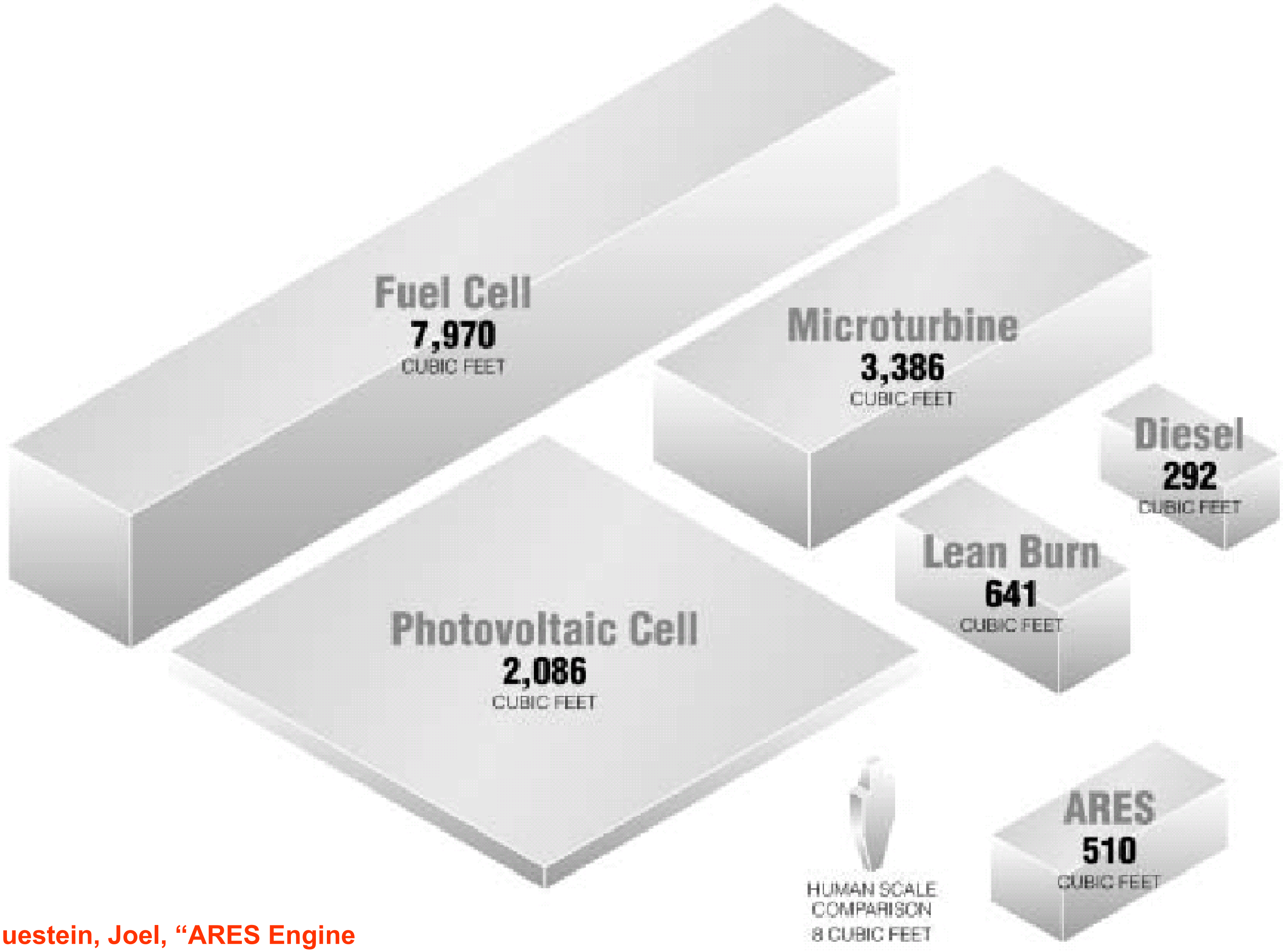


- Engines of many different sizes are being adapted to power generation to fulfill the need for distributed power
- 8.1 liter automotive engine

2000 kW Genset

- CAT G3520
- 86 liter engine designed as a stationary paltform

Physical Size - 500 kW Generator



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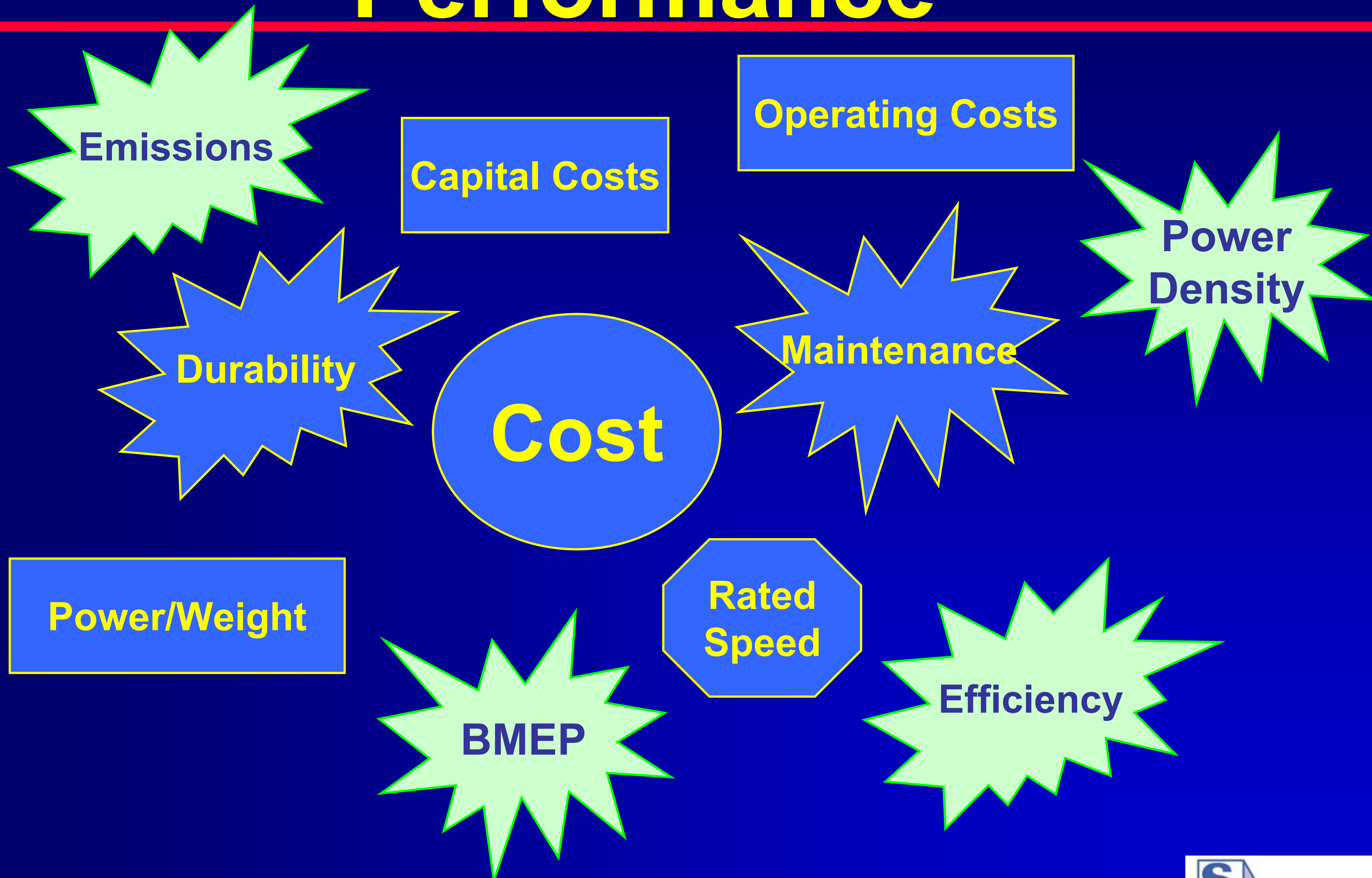
Manufacturers of Large Natural Gas Engines

- Caterpillar, Inc
- Cummins Engine Company, Inc
- Deutz
- Fairbanks Morse Engine
- Guascor
- Jenbacher
- MAN B&W
- Mitsubishi Heavy Industries
- MTU
- Niigata Engineering Company
- Perkins Engine Company
- Rolls-Royce
- Wärtsilä
- Waukesha Engine

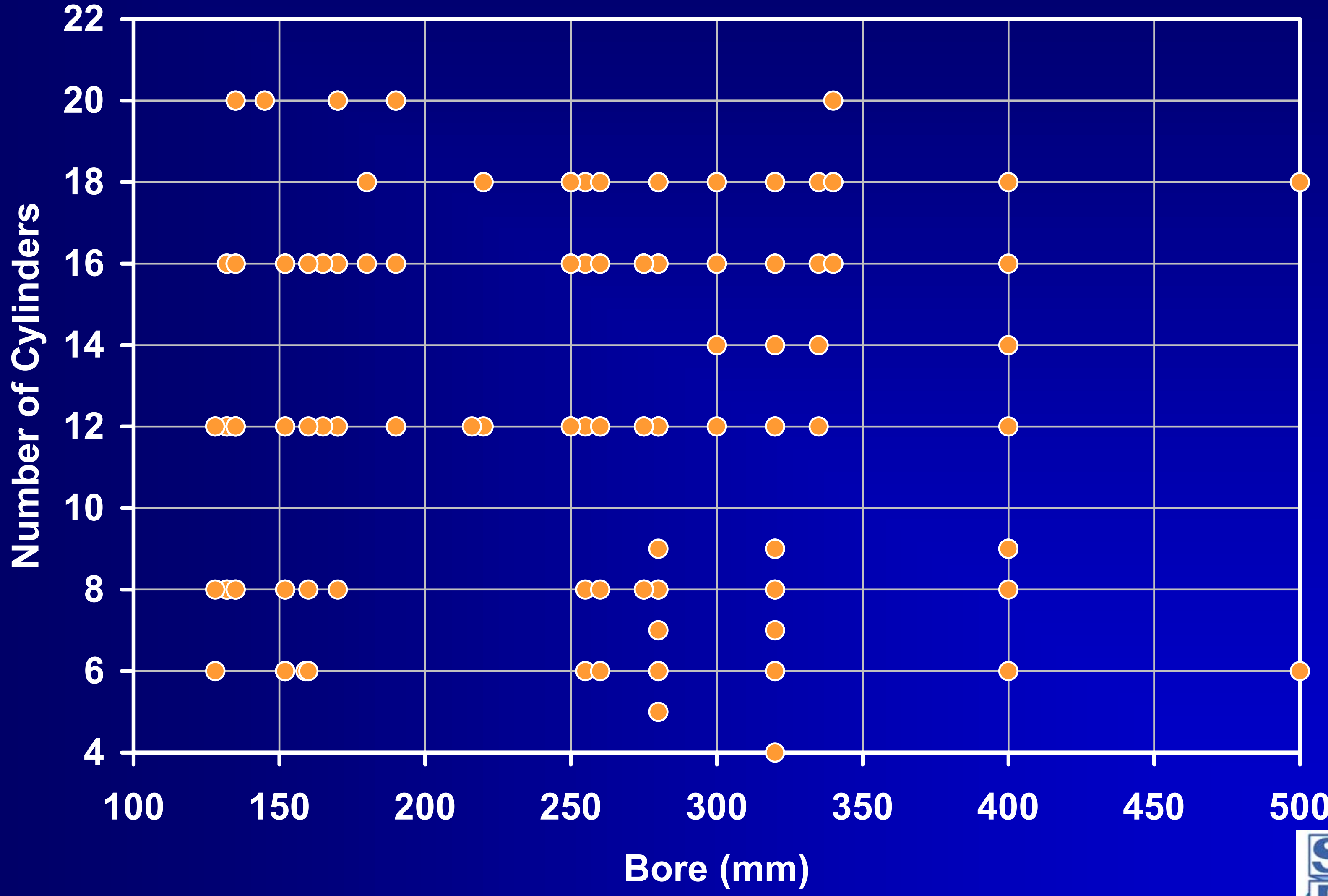
Aspects of Engine Performance



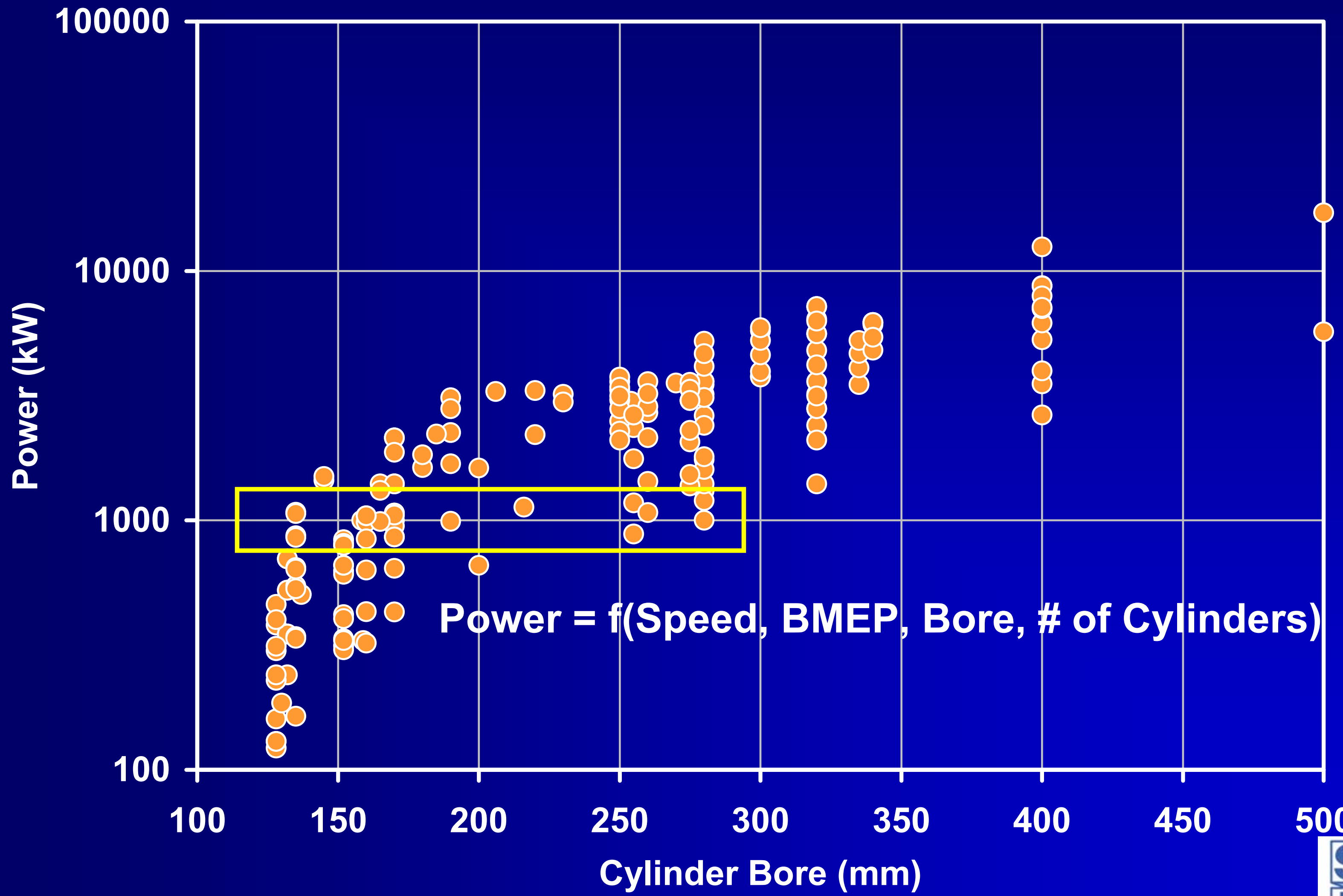
Engine Characteristics

- Number of Cylinders
- Bore (mm) (diameter of piston/cylinder)
- Speed (rpm)
- Power (MW)
- Power Density (kW/liter)
- BMEP (bar)

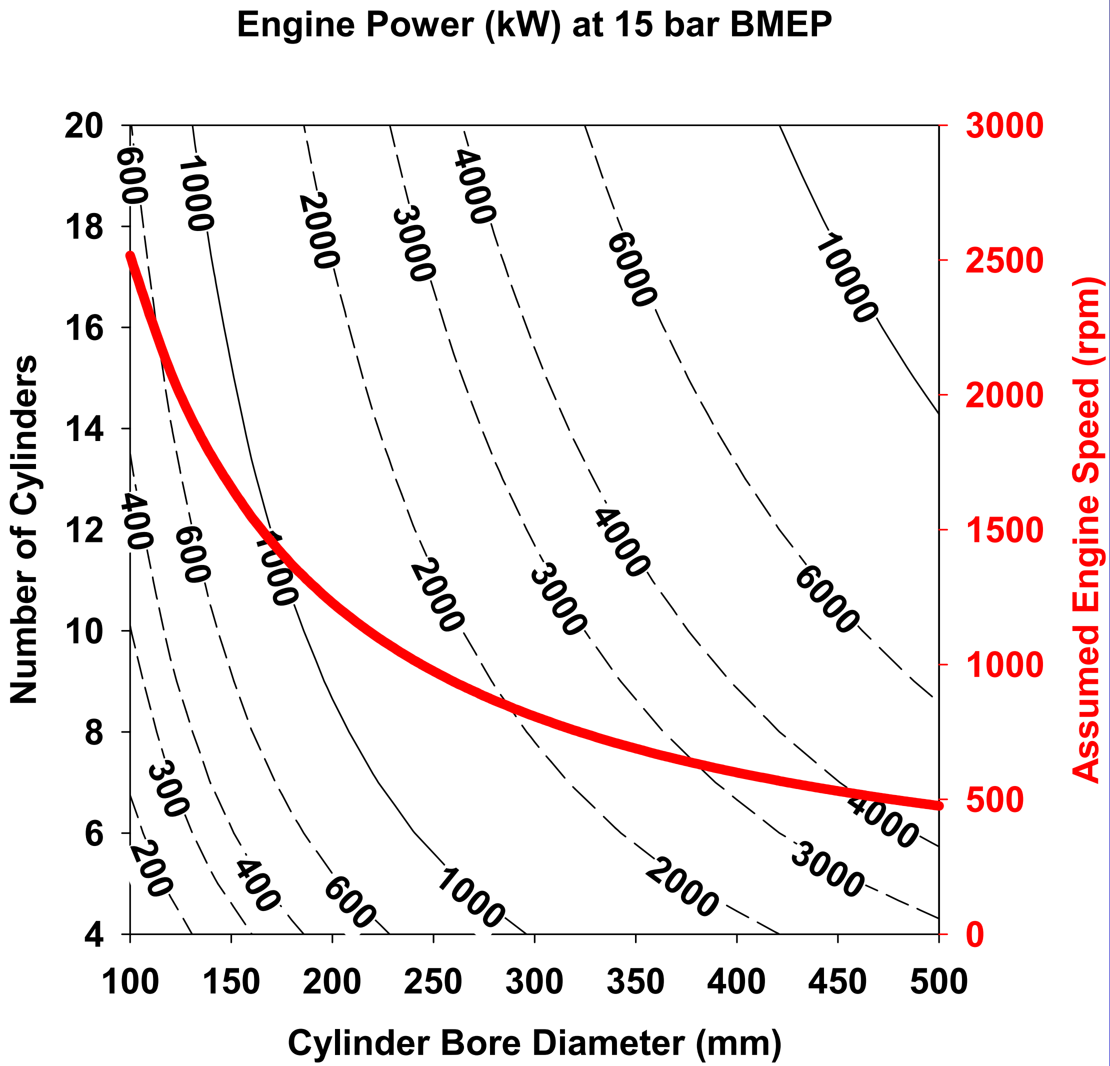
Number of Cylinders versus Engine Bore Diameter



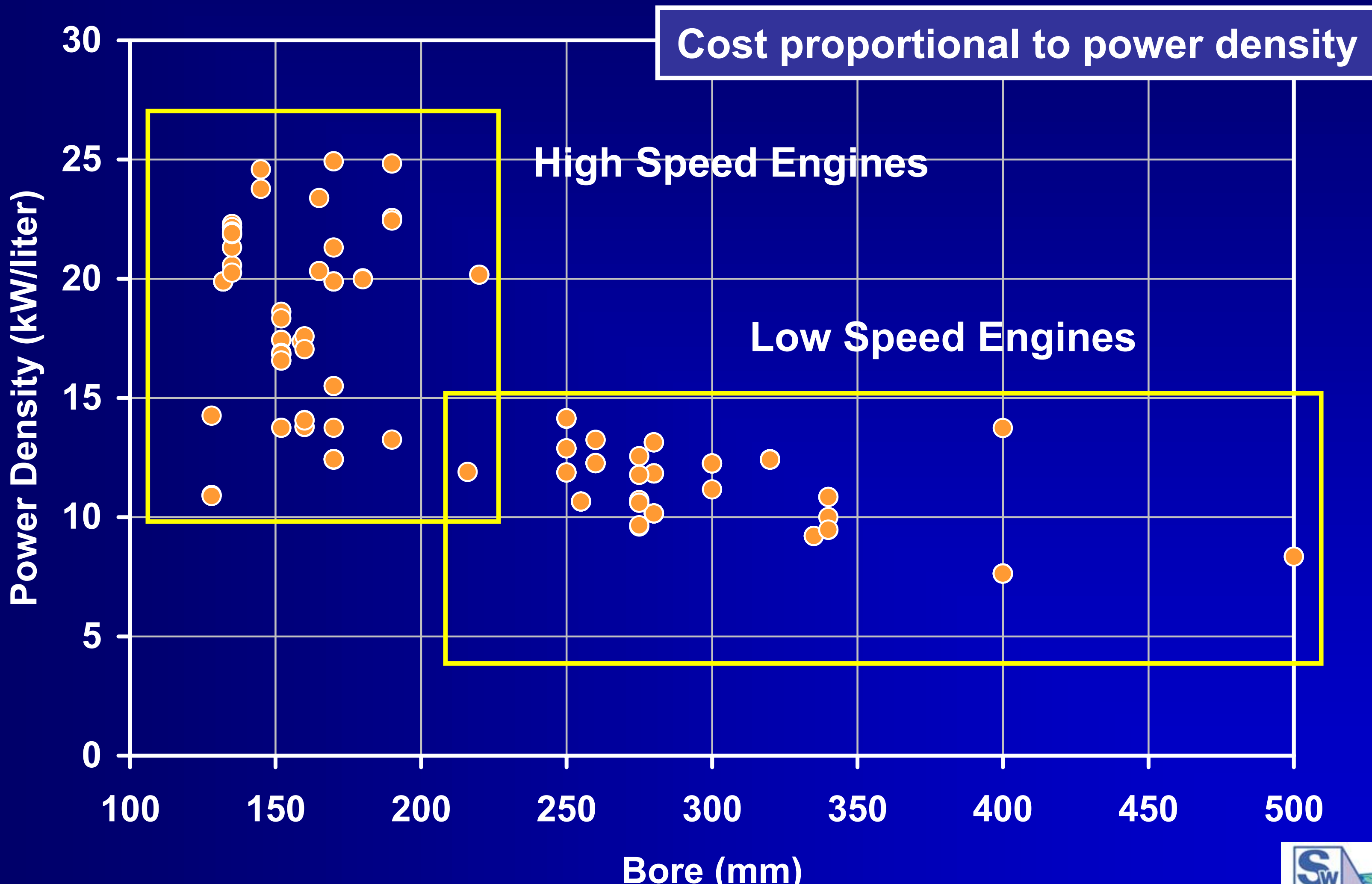
Engine Power versus Engine Bore Diameter



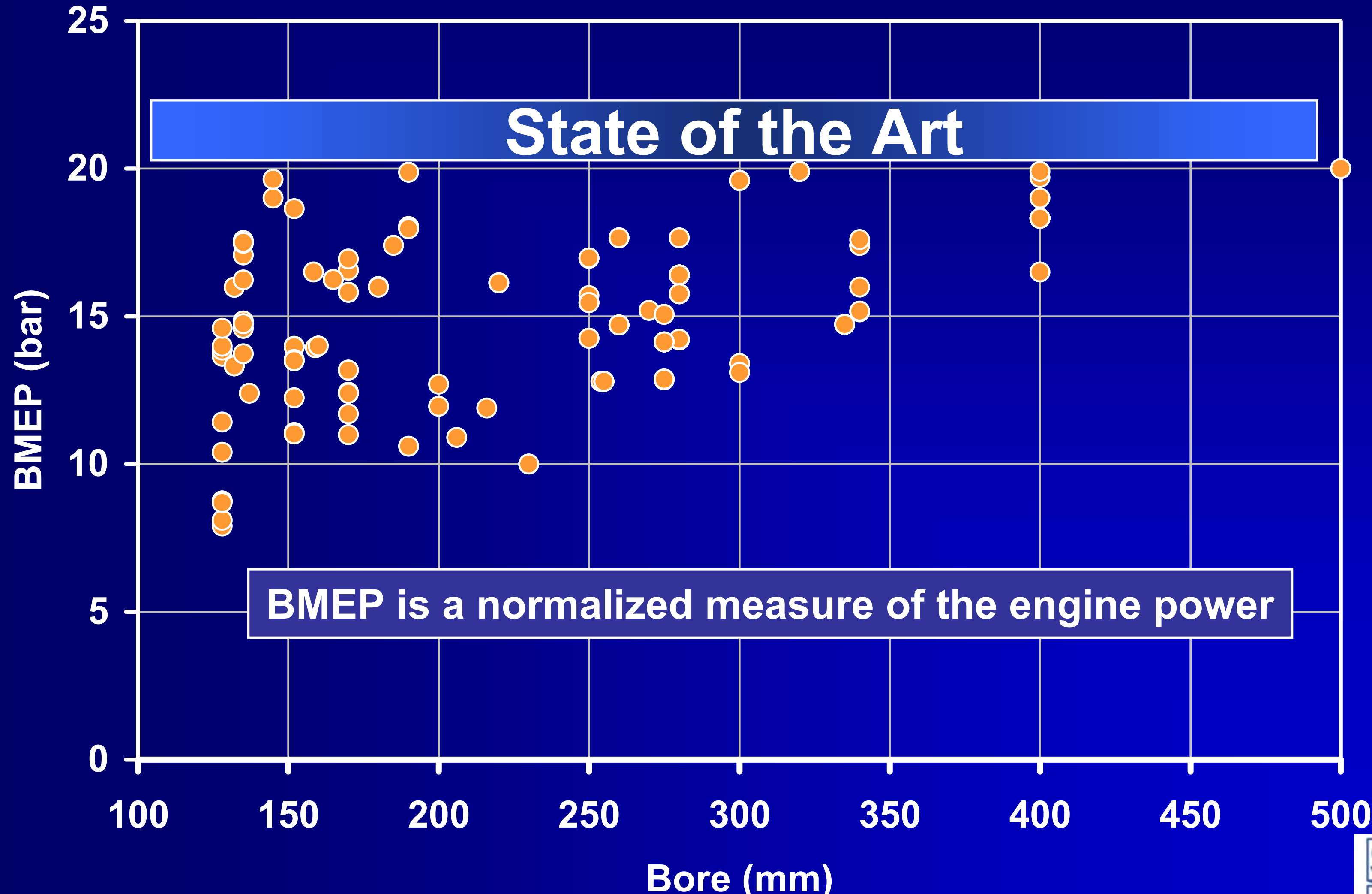
Power and Speed Range for Engines of Various Sizes



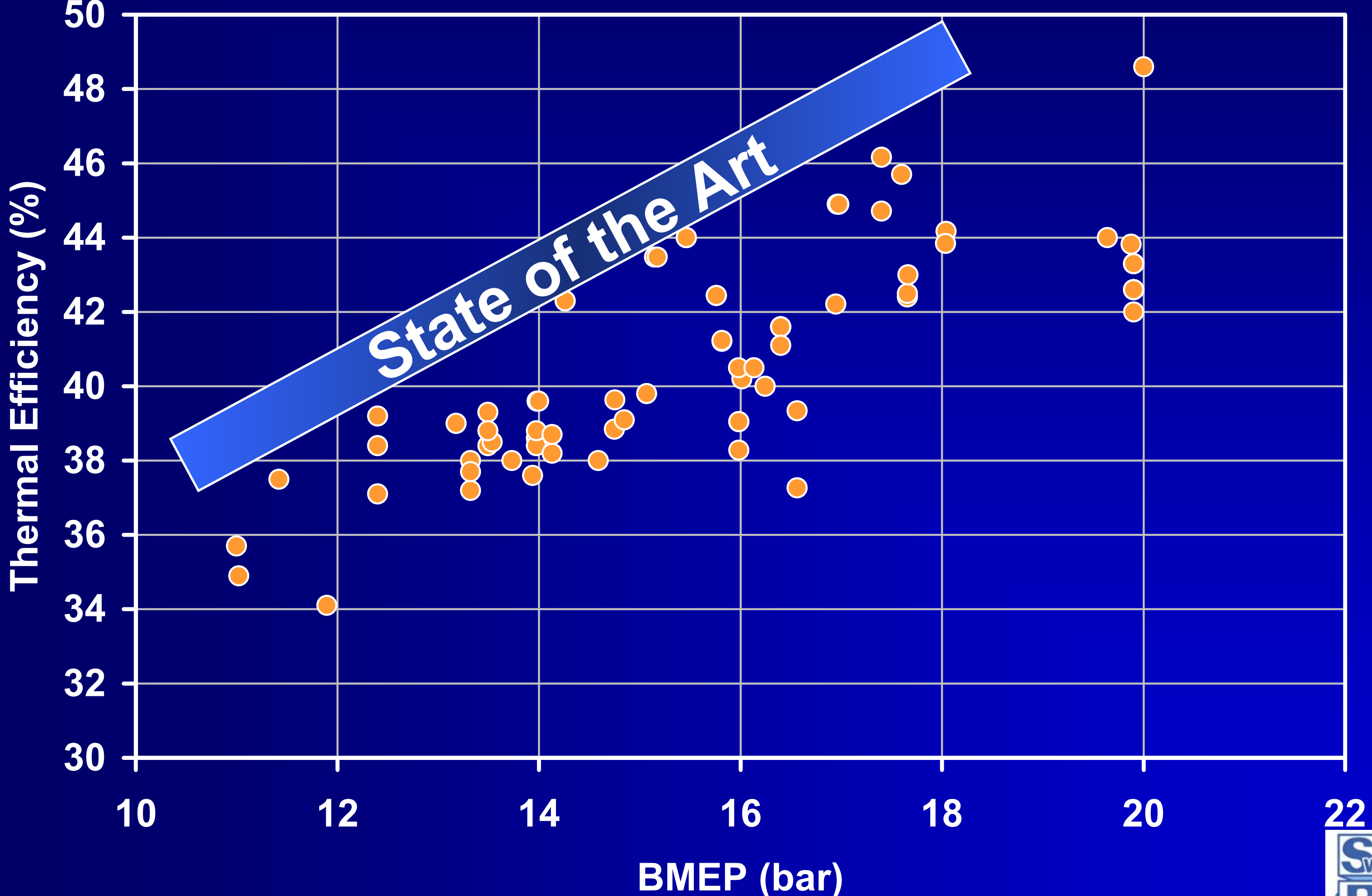
Power Density versus Engine Bore Diameter



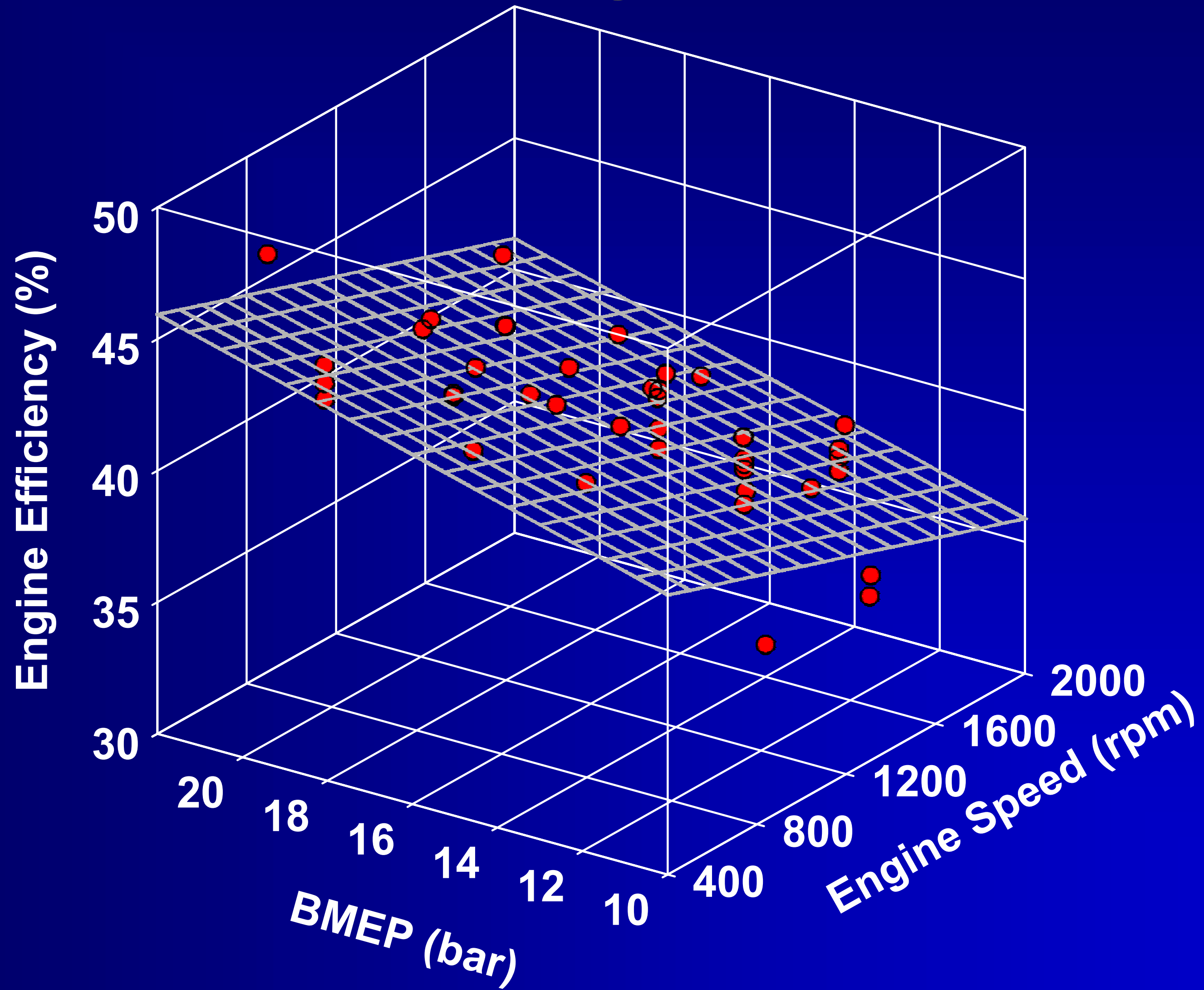
BMEP versus Engine Bore Diameter



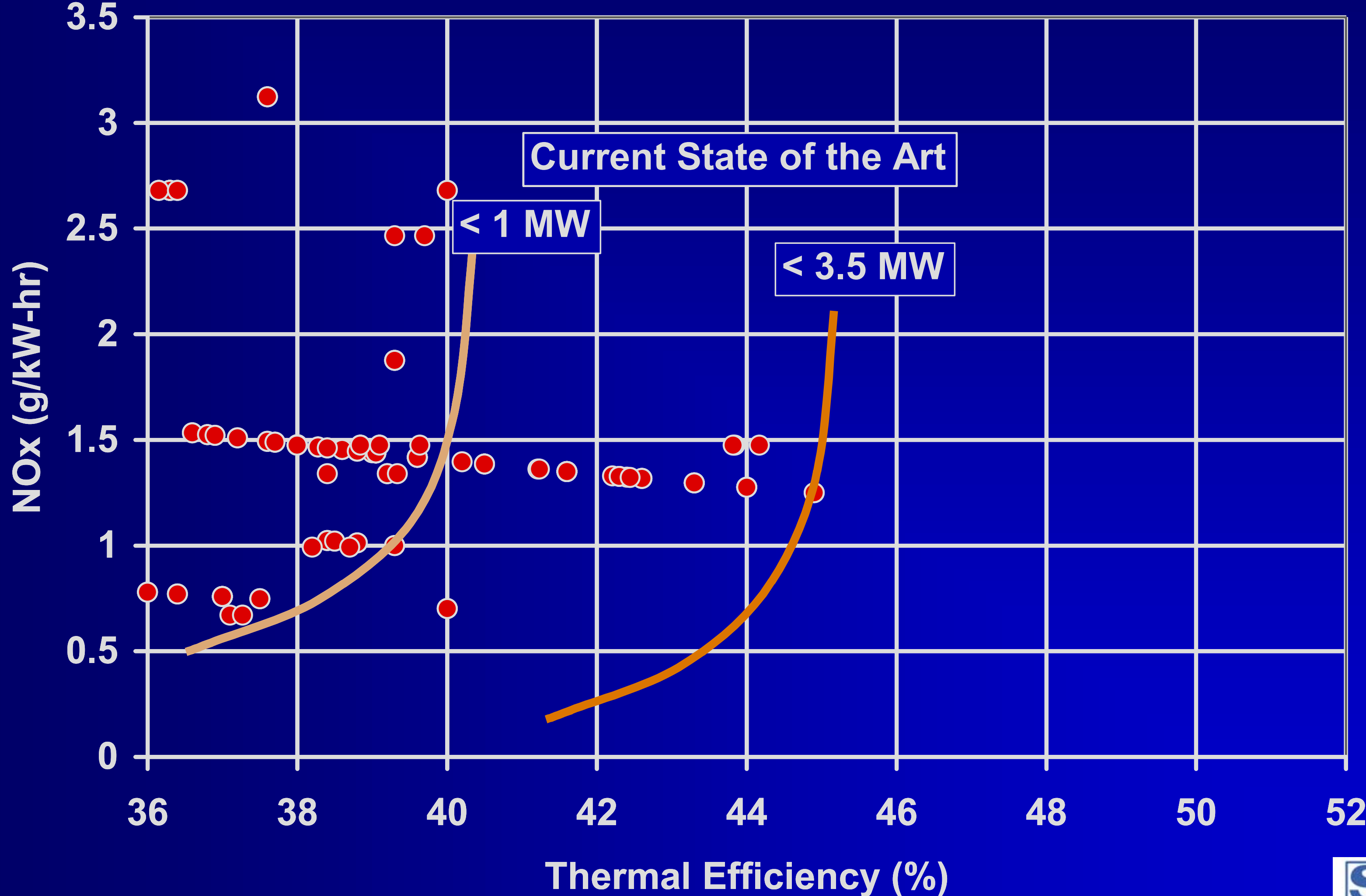
Impact of BMEP on Engine Efficiency (NOx < 1.2 g/bhp-hr)



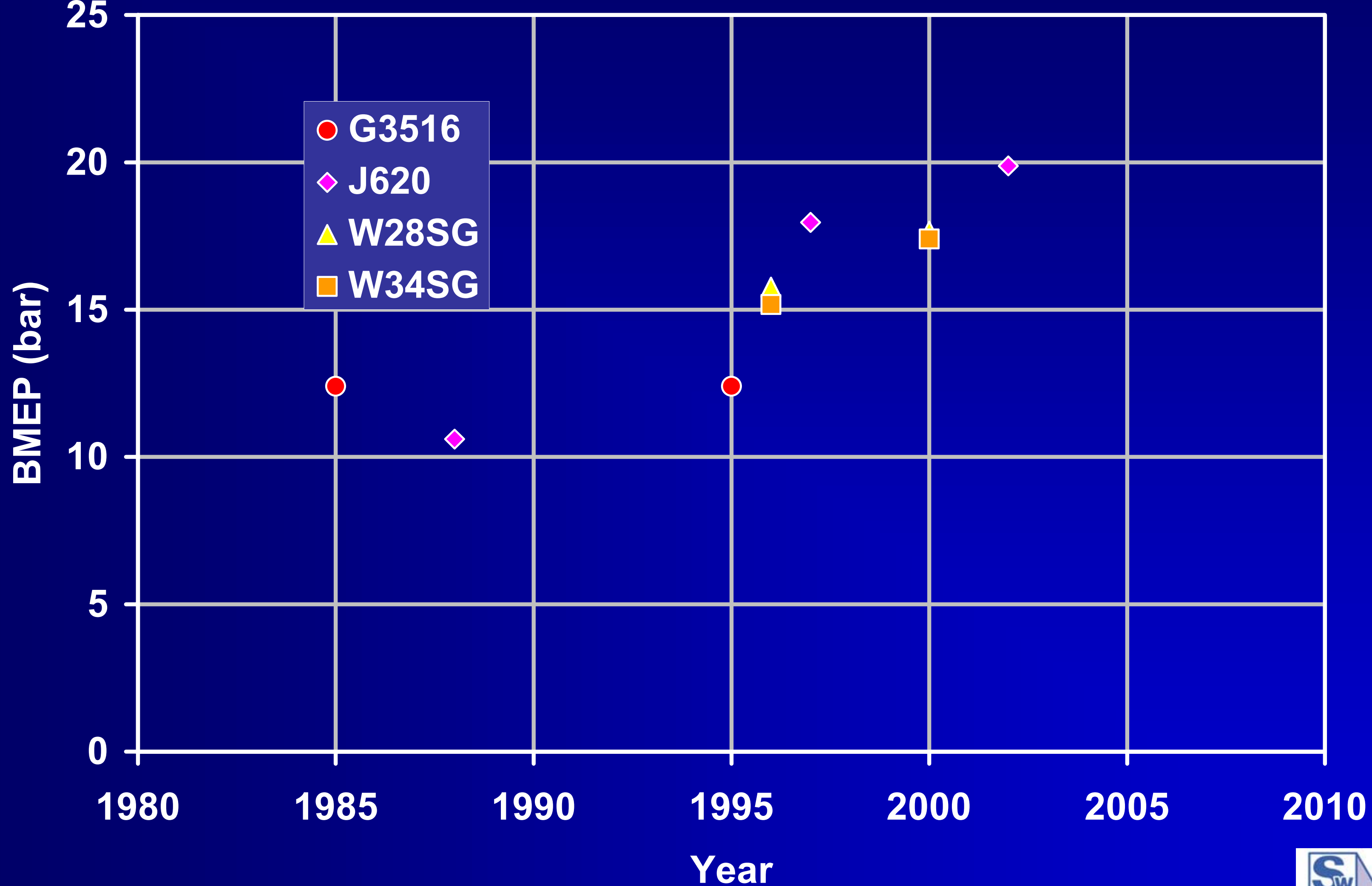
Impact of BMEP and Engine Speed on Engine Efficiency



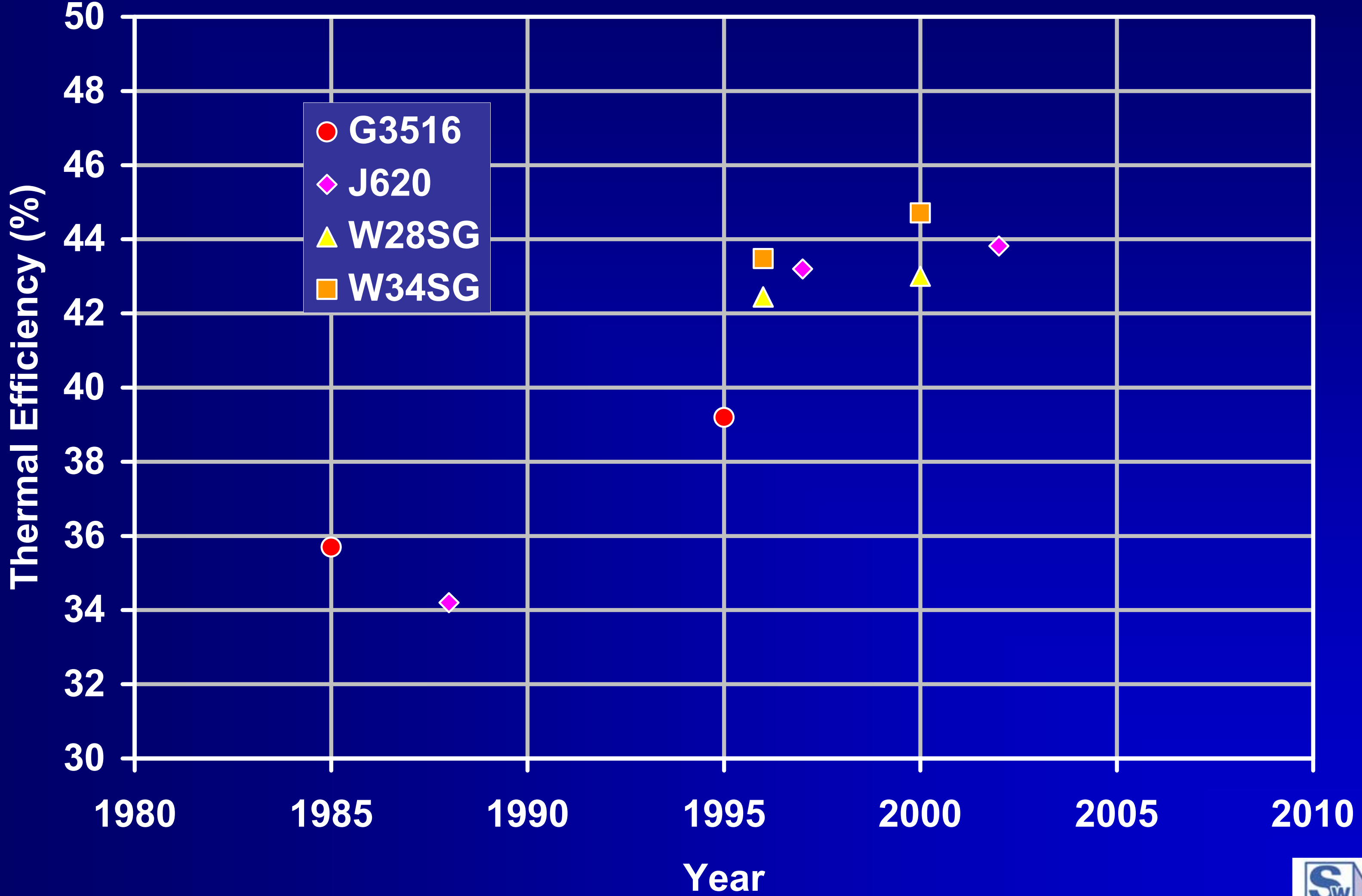
NOx-BTE Levels for 1-3 MW Engines



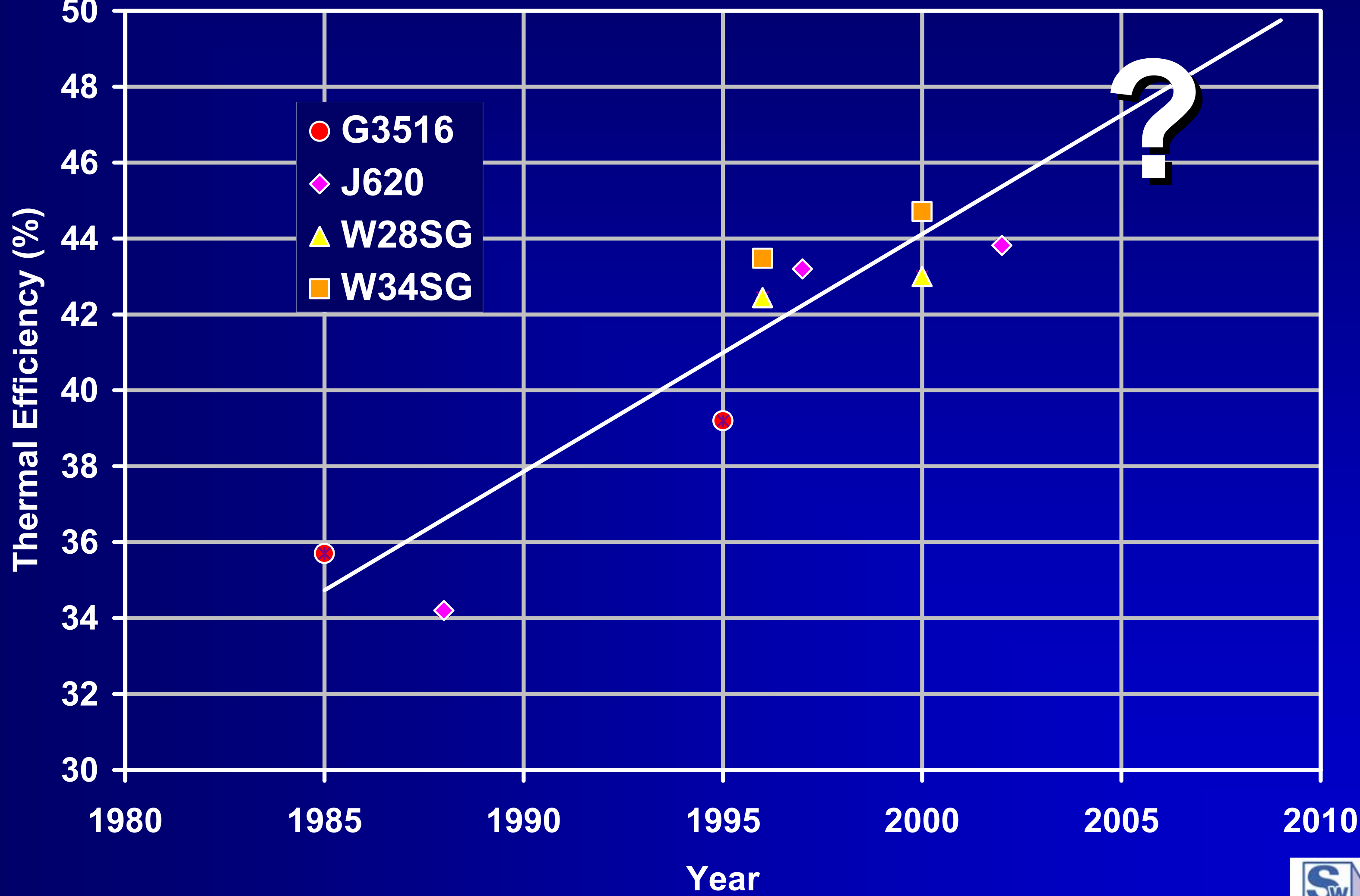
Brief Historical Trend for BMEP



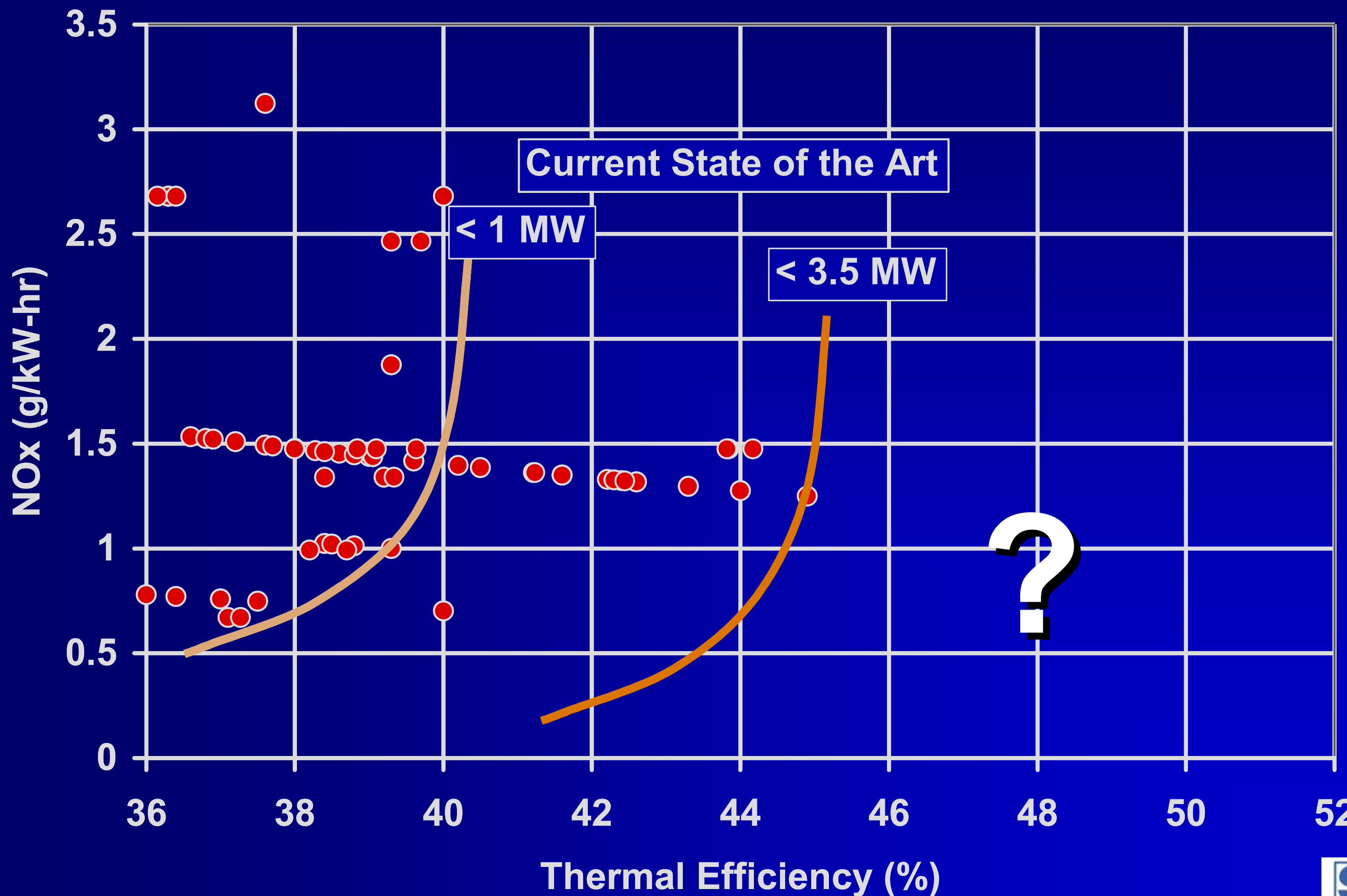
Brief Historical Trend for Thermal Efficiency



Future Trend for Thermal Efficiency



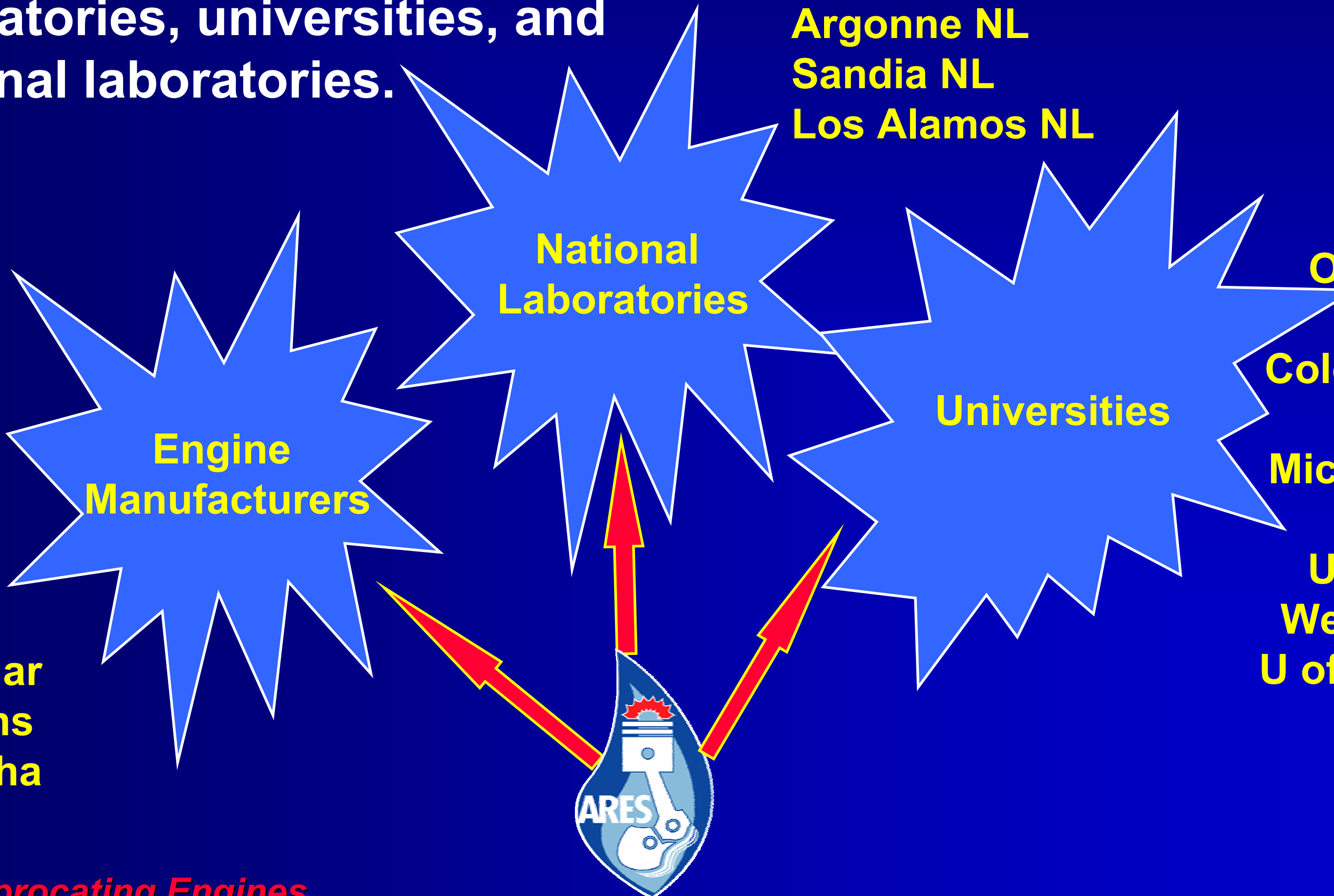
Future Development Targets for 1-3 MW Engines



ARES Program

ARES is a multi-faceted R&D program involving engine manufacturers, research laboratories, universities, and national laboratories.

National Energy Technology Laboratory
Southwest Research Institute
Oak Ridge NL
Argonne NL
Sandia NL
Los Alamos NL



Caterpillar
Cummins
Waukesha

Ohio State
Purdue
Colorado State
MIT
Michigan Tech
USC
U of Texas
West Virginia
U of Tennessee

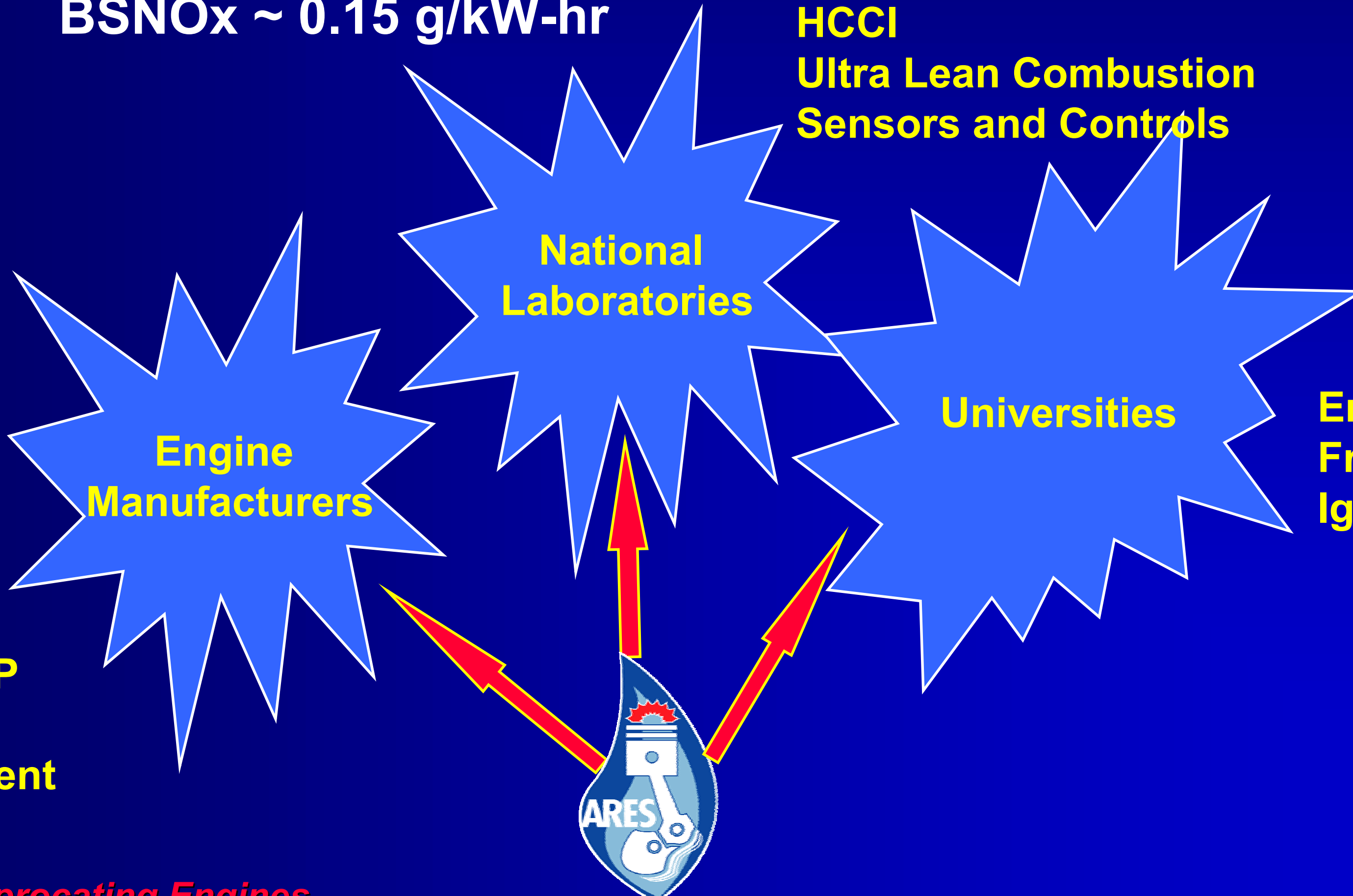
ARES Program

ARES Focused research areas

Short term targets ('05)

- Efficiency ~ 46%
- BSNOx ~ 0.15 g/kW-hr

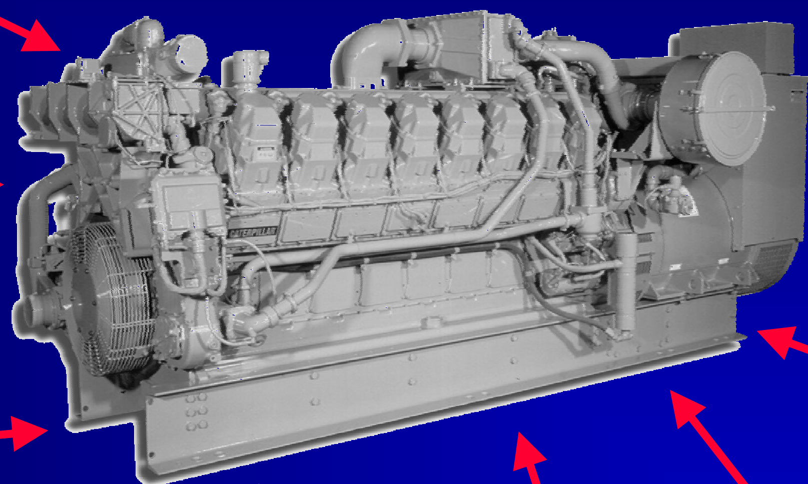
Knock Modeling
Dilute Combustion
HCCI
Ultra Lean Combustion
Sensors and Controls



Emissions
Friction
Ignition

High BMEP Engine Development

ARES Technologies



Combustion Chamber Geometry

Combustion of Dilute Mixtures

Modified or Alternative Engine Cycles

Exhaust Aftertreatment LNC, TWC, SCR

Water Injection

High Power Density

Multiple Source Ignition

Exhaust Energy Retention

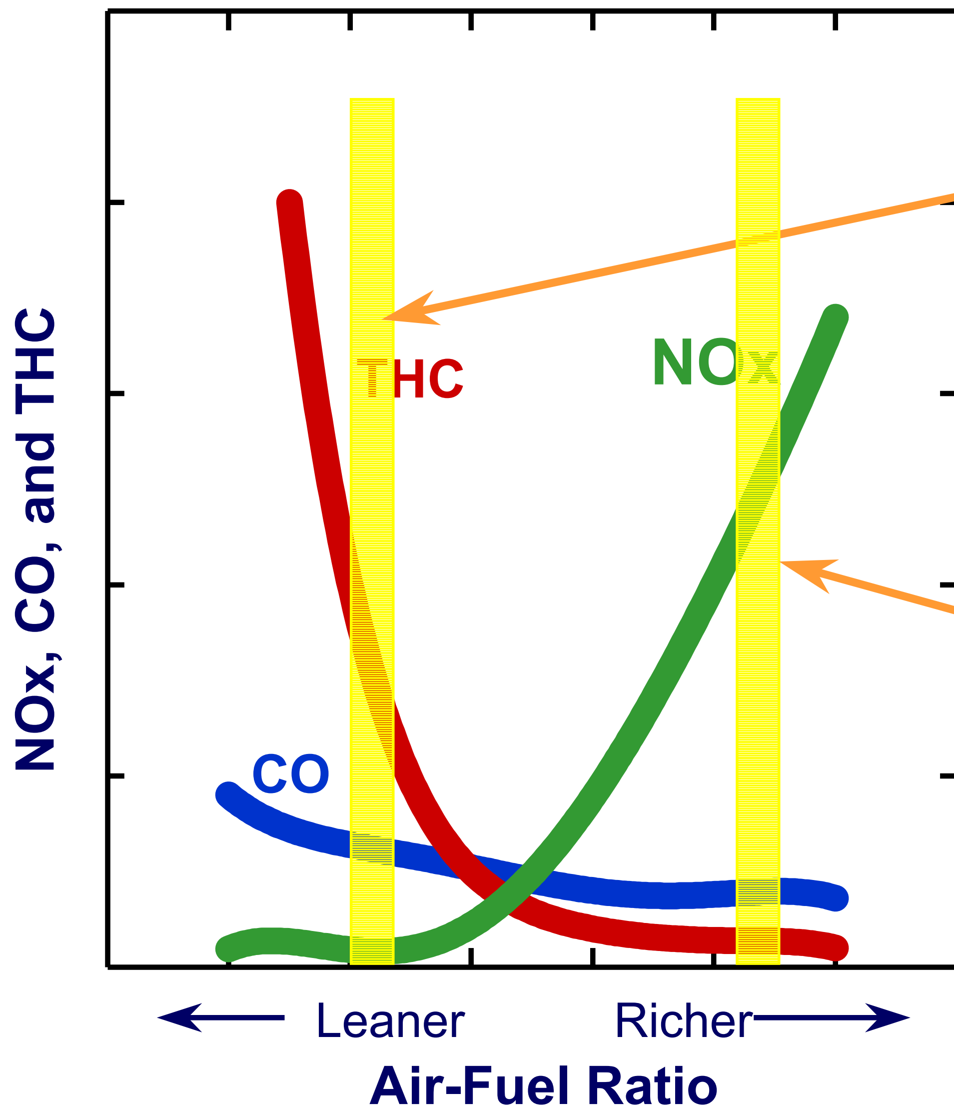
Turbo-compounding

Friction Reduction

Simplified Methane Combustion Chemistry

Reactants		Products
$CH_4 + 2\,O_2$	$\longrightarrow$	$CO_2 + 2\,H_2O$
+		
N_2	$\longrightarrow$	NO_x
Partial Oxidation	$\longrightarrow$	CO, CH_4

Emission Levels and Air-Fuel Ratio Operating Range for Gas Engine



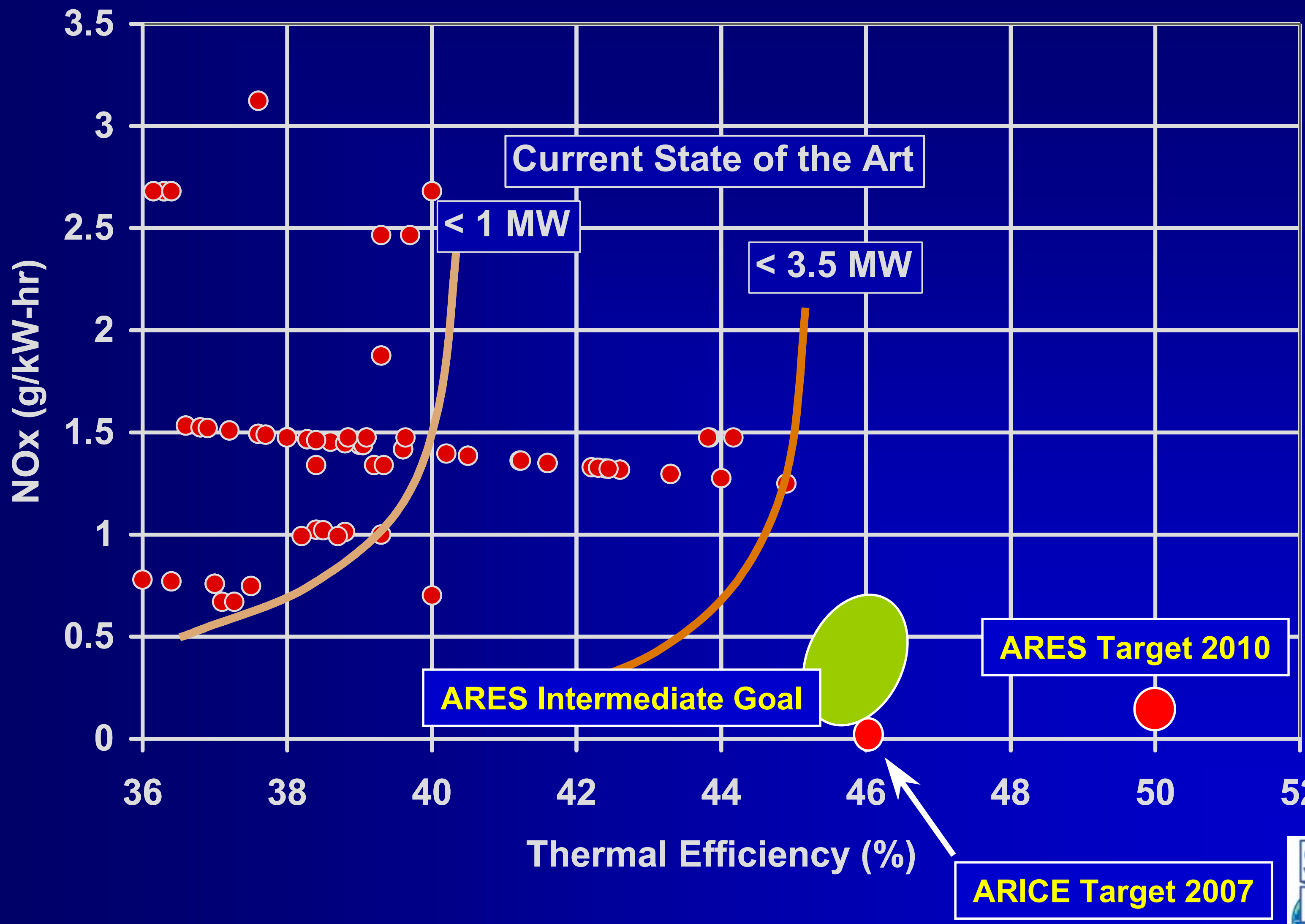
Lean Burn, combustion diluted with excess air, exhaust contains oxygen making catalytic aftertreatment of NOx problematic

Stoichiometric combustion Just enough air to consume all of the fuel, exhaust contains little oxygen enabling catalytic aftertreatment of NOx

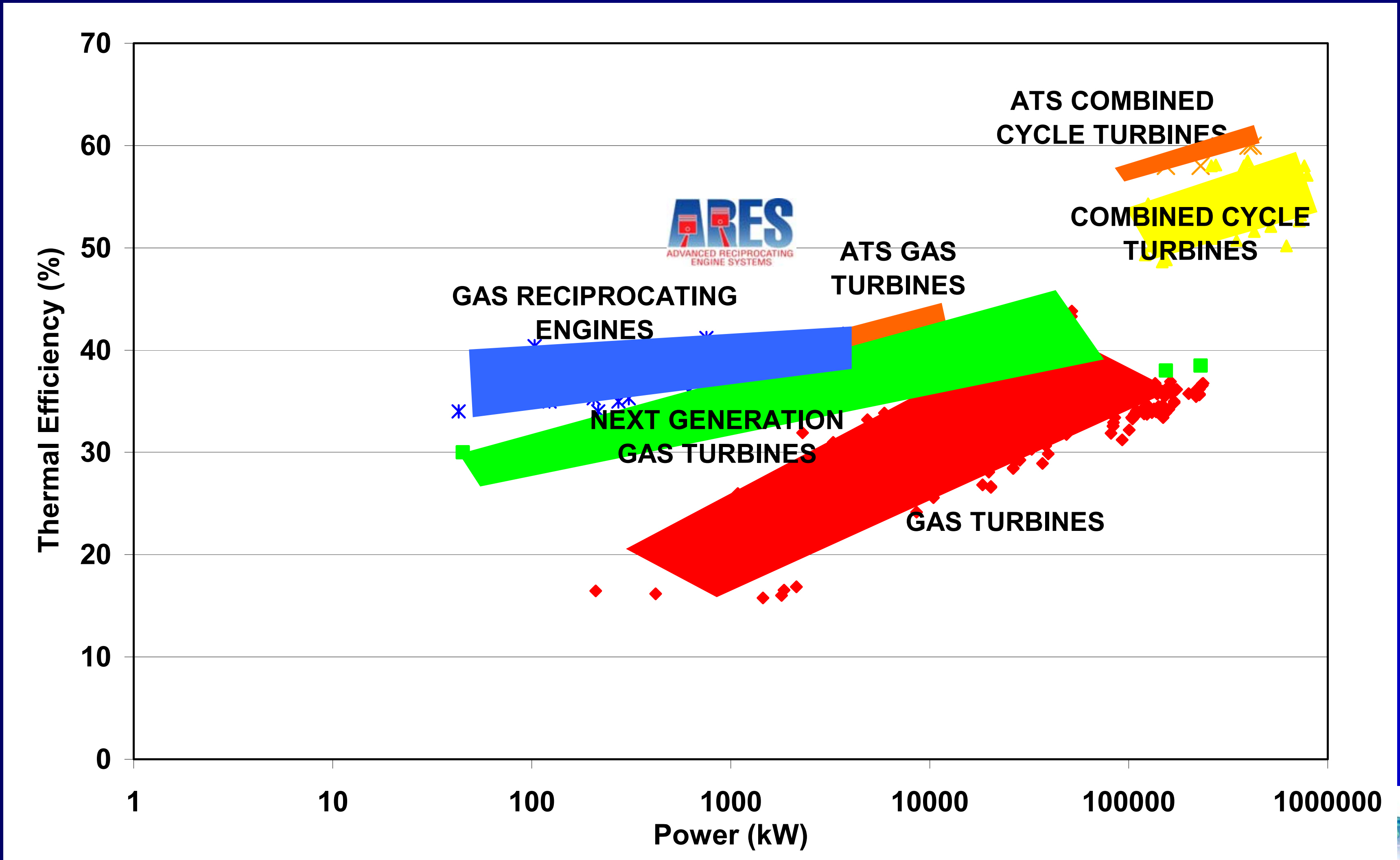
Aftertreatment

- Lean NO_x catalyst (LNC)
  - currently not a viable technology
- Selective catalytic reduction (SCR)
  - Viable for lean combustion, requires reductant (typically urea) that adds to operating costs
  - Potential for ammonia slip, control issue
  - 90-95% efficiency
- 3-way catalyst if no oxygen present in exhaust stream
  - Proven in light duty, shorter life applications
  - Low capital cost relative to SCR
  - 95-99% efficiency

Future Development Targets for 1-3 MW Engines



Gas Engine vs. Turbine Efficiency

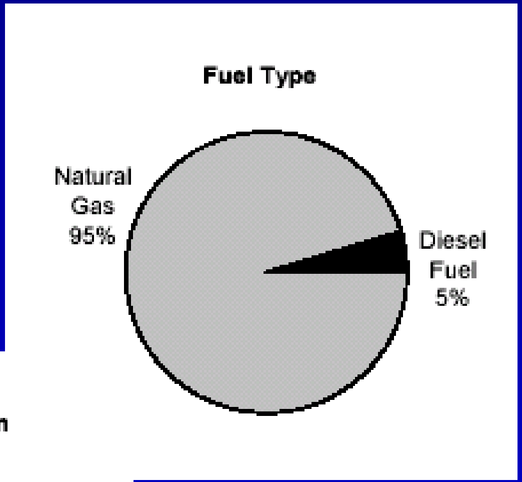


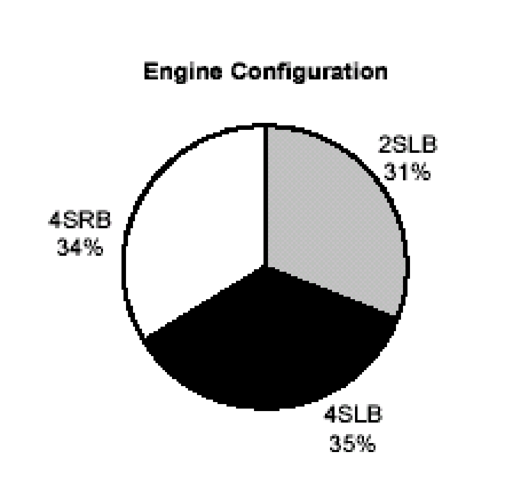
Upcoming Regulations

- "National Emissions Standards for Hazardous Air Pollutants (HAPS) for Stationary Reciprocating Internal Combustion Engines (RICE)" (NESHAP)
- Purpose
  - Set regulatory standards for HAPs or Air Toxic Emissions from RICE
  - HAPs of most concern
    - —***formaldehyde***, acrolein, methanol, acetaldehyde

RICE - Subcategories

- Emergency power/limited use
- Landfill gas or digester gas combusted as primary fuel
- Engines less than 500 brake horsepower
- Other
  - Four stroke lean burn (4SLB)
  - Four stroke rich burn (4SRB)
  - Compression Ignition (CI)
  - Two stroke lean burn (2SLB)





Engine Inventory

RICE - Applicability

- The rule will apply to each stationary <u>RICE located at a major source of HAP</u> above 500HP
- Stationary RICE meeting any of the following criteria have no requirements except for an initial notification requirement:
  - Emergency power/limited use units
  - Units that combust digester or landfill gas as primary fuel
- Existing 2SLB, existing 4SLB, and existing CI have *no* requirements
- In summary, <u>existing 4SRB</u> and <u>all new</u> RICE have regulatory requirements

Analysis

- Rule basically requires an oxidation catalyst for new engines
- Most immediate impact in gas transmission industry - largest single concentration of RICE at major sources
- Many applications will not be greater than 500 hp or will not be located at major sources - so this rule will not apply

RICE MACT Schedule

- Proposed in December 19, 2002
- Comments until February 20, 2003
- Promulgation in February 28, 2004
- Engines installed after proposal must meet final rule

Summary

- Gas engine efficiency will continue to improve even as emission levels continue to decrease
- Concerted development efforts are required for continuous improvement to overcome technical barriers
- Advanced concepts will be required to achieve and exceed the projected development targets

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Thank you for your attention!